LA-UR-21-24249
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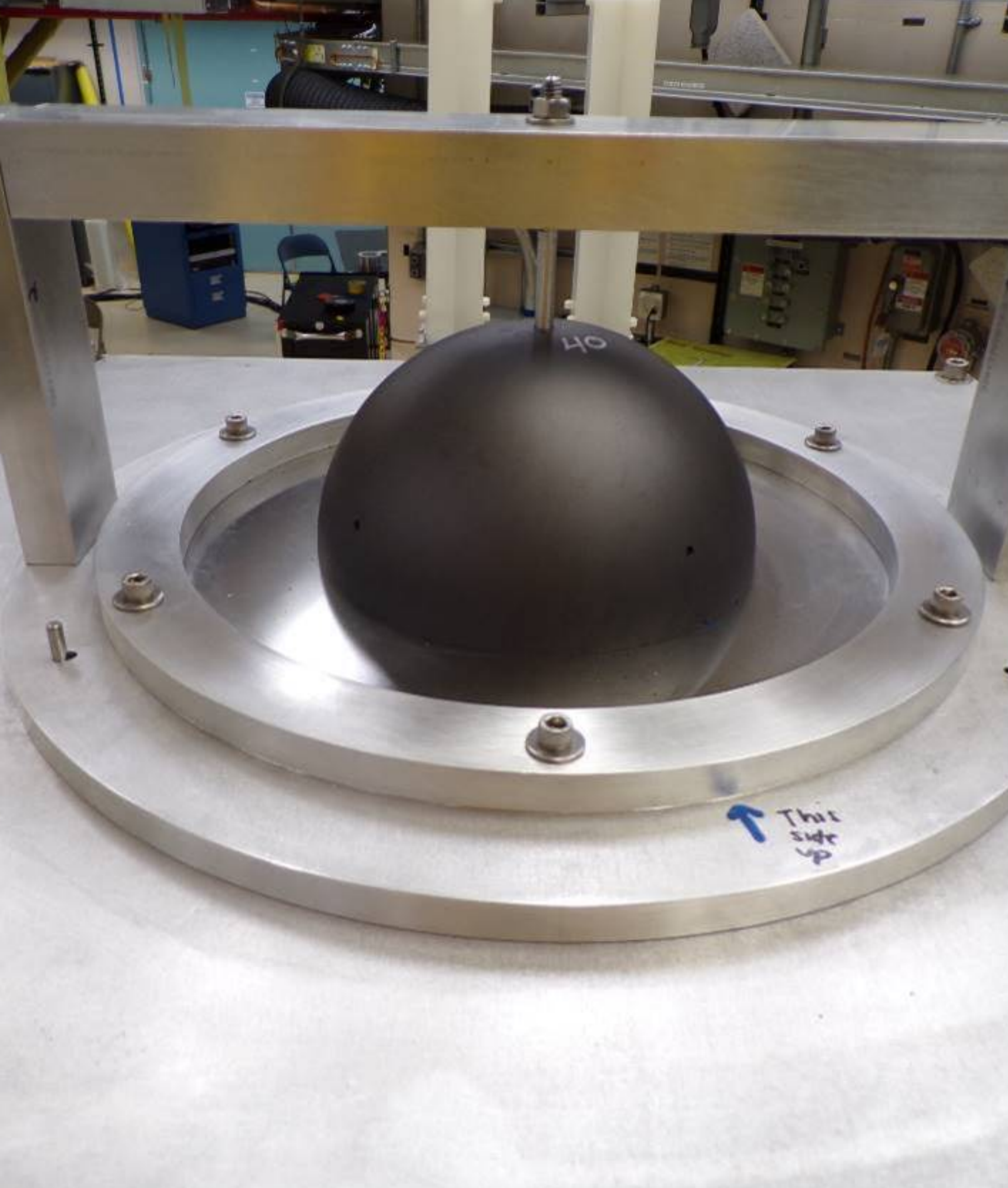
Intended for: Web

Issued: 2021-05-03



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MUSiC: Measurement of Uranium Subcritical and Critical (IER 488)

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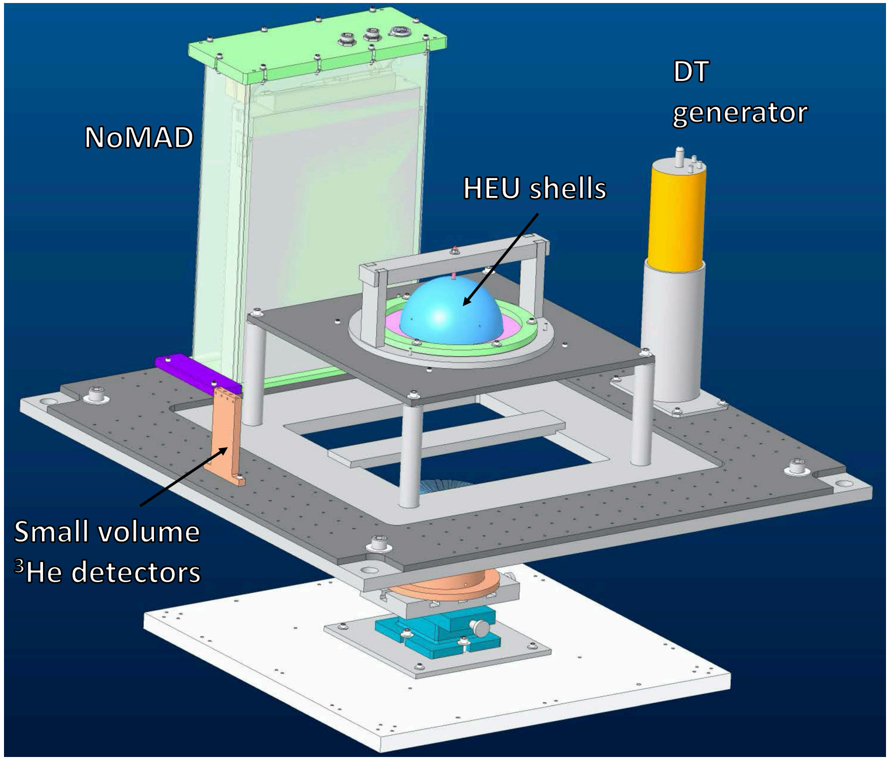
2/24/2021

Measurement of Uranium Subcritical and Critical (MUSiC)

- Measurements of bare, HEU system
  - Rocky Flats shells – variable mass
  - Ten configurations will be measured, spanning from deeply subcritical to critical (i.e., it is a measurement of similar systems with different reactivities)
- Key benefits of MUSiC:
  - Large range of reactivities (subcrit to crit)
    - First measurement of a simple/fast system that covers such a range to be submitted to ICSBEP
    - Subcritical benchmarks – useful for testing correlated fission physics (CGMF, FREYA)
  - Simple HEU system (new Lady Godiva HMF001) – valuable for nuclear data validation
  - Multiple detector systems and measurement methods
    - Provide results independent of the detector system
    - Demonstrate the suitability of organic scintillators for future benchmark measurements

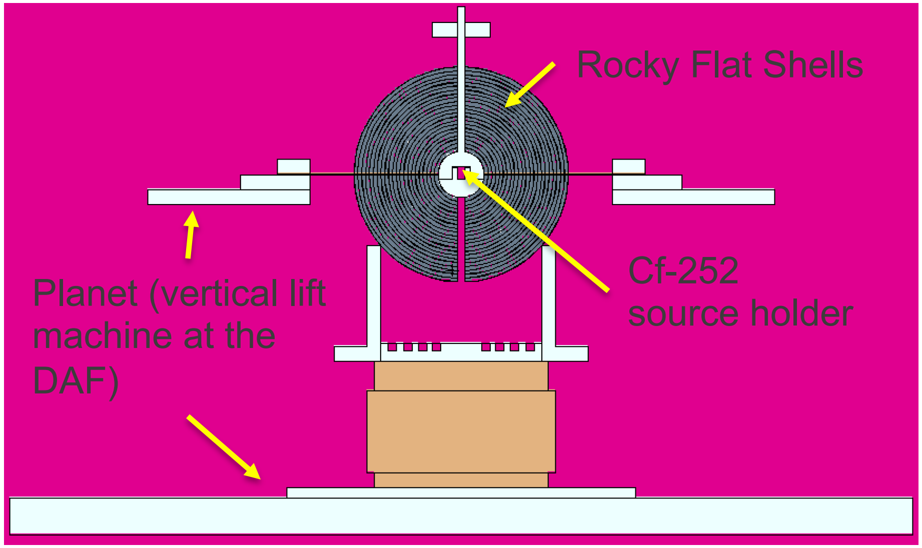


Rocky Flats HEU hemisphere shells

- 93.16% U-235
- ~0.3 cm thick
- Variable radius between ~2 cm and 10 cm
- MUSiC configurations:

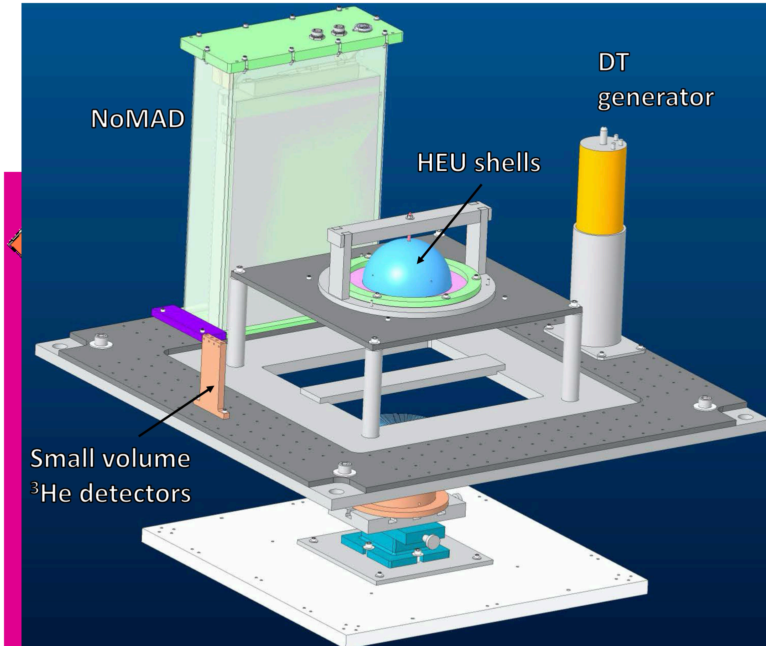
Simulated configurations

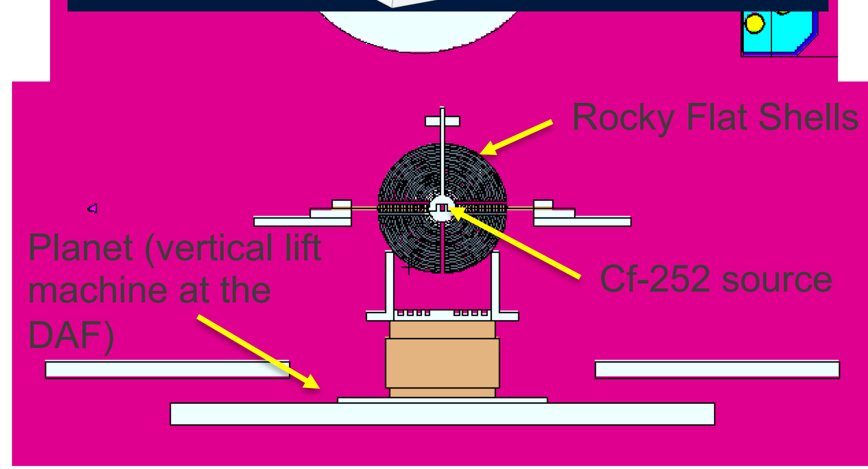
Configuration	Mass (kg)	k_{eff}
1	15.723	0.64925
2	21.832	0.72715
3	33.552	0.83854
4	38.243	0.87888
5	47.925	0.92428
6	54.642	0.97914
7	60.190	0.99179
8	60.657	1.00228
9	61.009	1.01077
10	67.082	1.02448



Measurement details

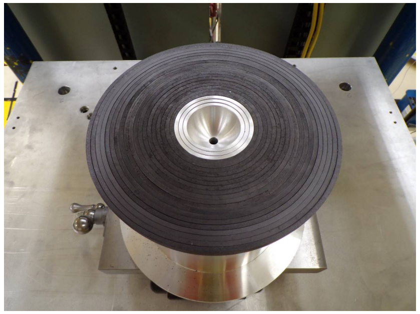
- Induced fission driven by:
  - DT generator
  - Cf-252
- Detectors
  - NoMAD
    - 15 He-3 tubes embedded in high density polyethylene
    - Portable
  - Array of 4 small volume He-3 detectors
    - High pressure (40 atm vs 10 atm for NoMAD)
    - Fast recovery speed – suitable for Rossi-α measurements
  - **Array of 8, 2”×2” EJ-309 detectors**
    - New detection system for NCERC
    - Direct detection of fast neutrons
    - No moderation, fast response → ideal for bare systems





Approach to critical (12/20)

- Measurements to determine the final configurations were perform in December 2020
  - Approach to critical
  - Remeasured shell masses (losses)
- Changes between simulated and experimentally determined configurations:



Experimentally determined configurations

Configuration	Mass (kg)	k_{eff}
1	13.0428	0.64
2	21.6432	0.74
3	29.0415	0.81
4	37.9617	0.88
5	42.9722	0.91
6	48.4099	0.95
7	54.2785	0.98

Simulated configurations

Configuration	Mass (kg)	k_{eff}
1	15.723	0.64925
2	21.832	0.72715
3	33.552	0.83854
4	38.243	0.87888
5	47.925	0.92428
6	54.642	0.97914
7	60.190	0.99179
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10	67.082	1.02448

The Rossi-α method

- Goal: infer reactivity from a measurement of the prompt neutron decay
  - Prompt neutron decay constant (α) – rate of prompt neutron population change with time (units of inverse time)
  - Represents an eigenvalue characteristic of a system that can (in principle) be calculated and measured
- Assumptions in relation to reactivity
  - Based on point kinetic reactor model
  - The spatial flux is time independent
  - Not true for subcritical systems, but it is a reasonable approximation down to some (?) subcritical value of k_{eff}
- Method compliments Feyman variance-to-mean and pulsed source techniques

Reactivity and k_{eff}:

$$\rho = \frac{k_{eff} - 1}{k_{eff}}$$

Reactivity and α:

$$\rho = \beta_{eff} - \alpha\Lambda$$

β_{eff} – effective delayed neutron fraction

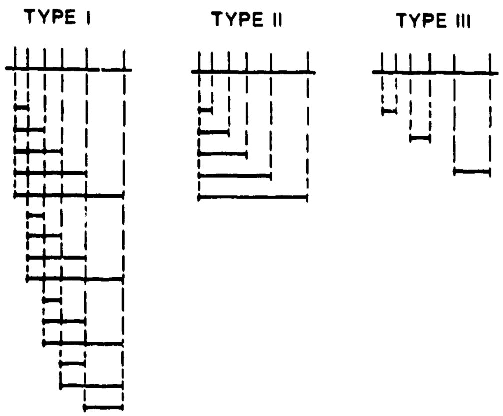
Λ – mean neutron generation time

Implementation of the Rossi-α method

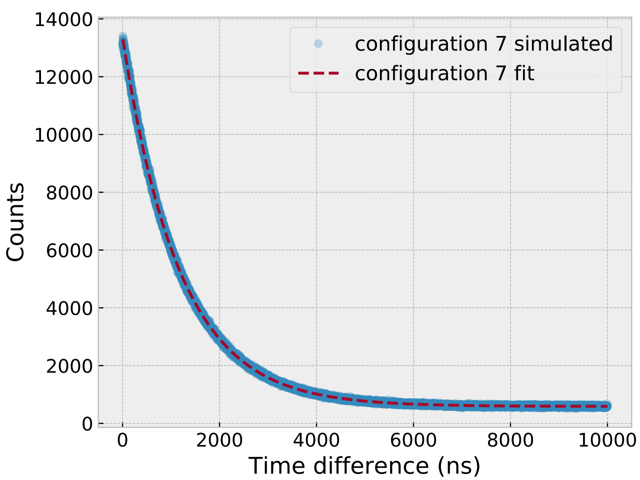
- Simple measurement
  - Collect neutron interaction times using the detectors
  - Analyze events within a selected time window (or reset time)
  - Calculate time difference between interactions (type 1 binning)
  - Number of counts will be correlated to the time difference
  - Estimate α by fitting the curve with

$$p(t) = Ae^{-\alpha t} + B \qquad [1]$$

  - Accurate for the time dependence of the prompt neutron decay for a fissioning assembly at low power (need to avoid overlapping fission chains)



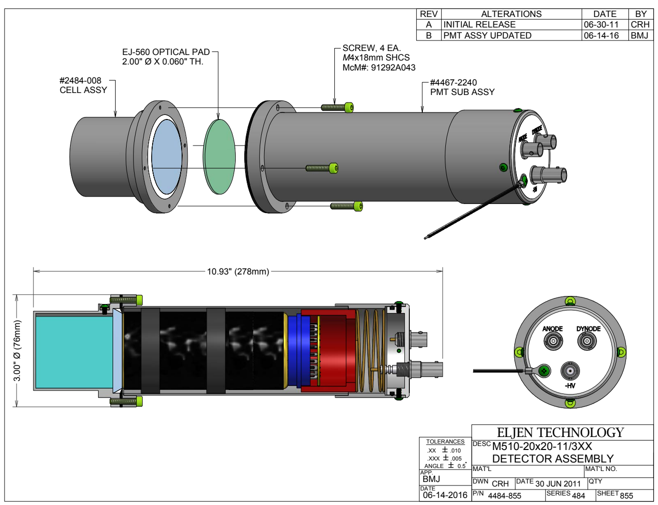
Binning types. Figure from [1].

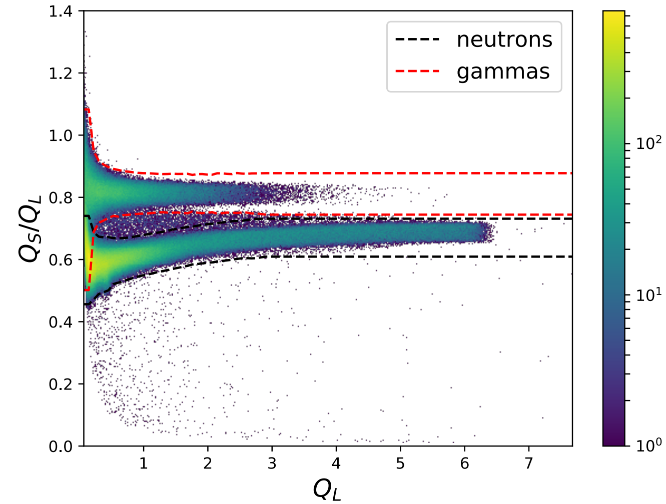


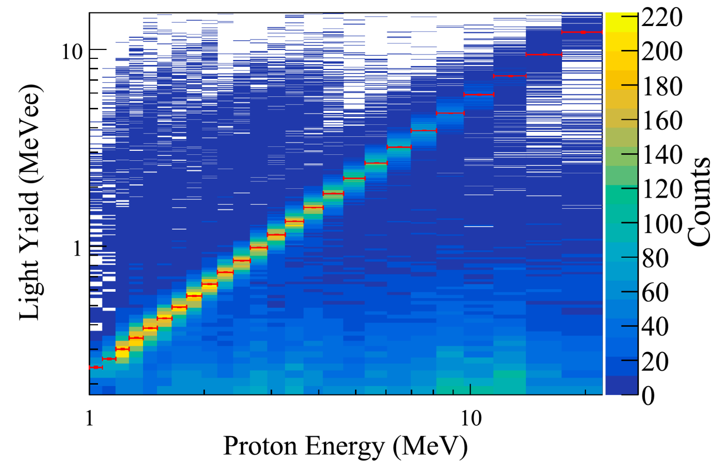
[1] Hansen, Gordon E. *Rossi Alpha Method*. No. LA-UR-85-4176; CONF-8508105-7. Los Alamos National Lab., NM (USA), 1985.

EJ-309 liquid organic scintillators

- Time resolution (~900 ps)
  - Excellent for neutron noise measurements
- Pulse shape discrimination – eliminate gamma interactions
- Energy information is also available – spectroscopy





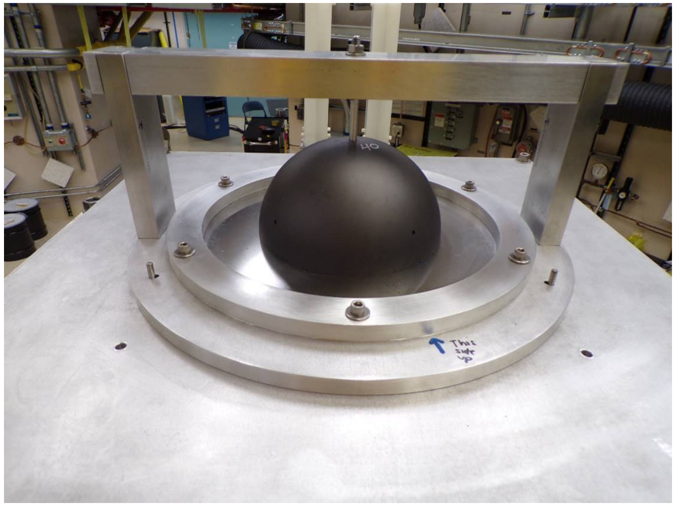


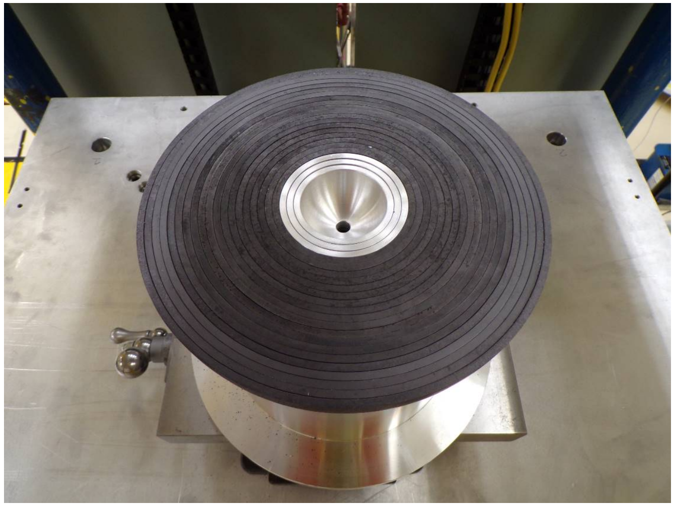
From [2].

[2] Brown, J. A., Goldblum, B. L., Laplace, T. A., Harrig, K. P., Bernstein, L. A., Bleuel, D. L., & Marleau, P. (2018). Proton light yield in organic scintillators using a double time-of-flight technique. *Journal of Applied Physics*, *124*(4), 045101.

Conclusions and future work

- MUSiC
  - Bare, HEU measurements covering a large range of reactivities
  - Multiple detector systems and analysis methods are being used/implemented to obtain detector-independent results
- Future work
  - Measurements: February – March 2021
  - Simulations
    - Event-by-event simulations of Rossi-α
    - ACODE – under development for MCNP6
    - MCATK – can be used to calculate subcritical α-eigenvalues





Acknowledgements

- This work was supported by the DOE Nuclear Criticality Safety Program, funded and managed by the National Nuclear Security Administration for the Department of Energy

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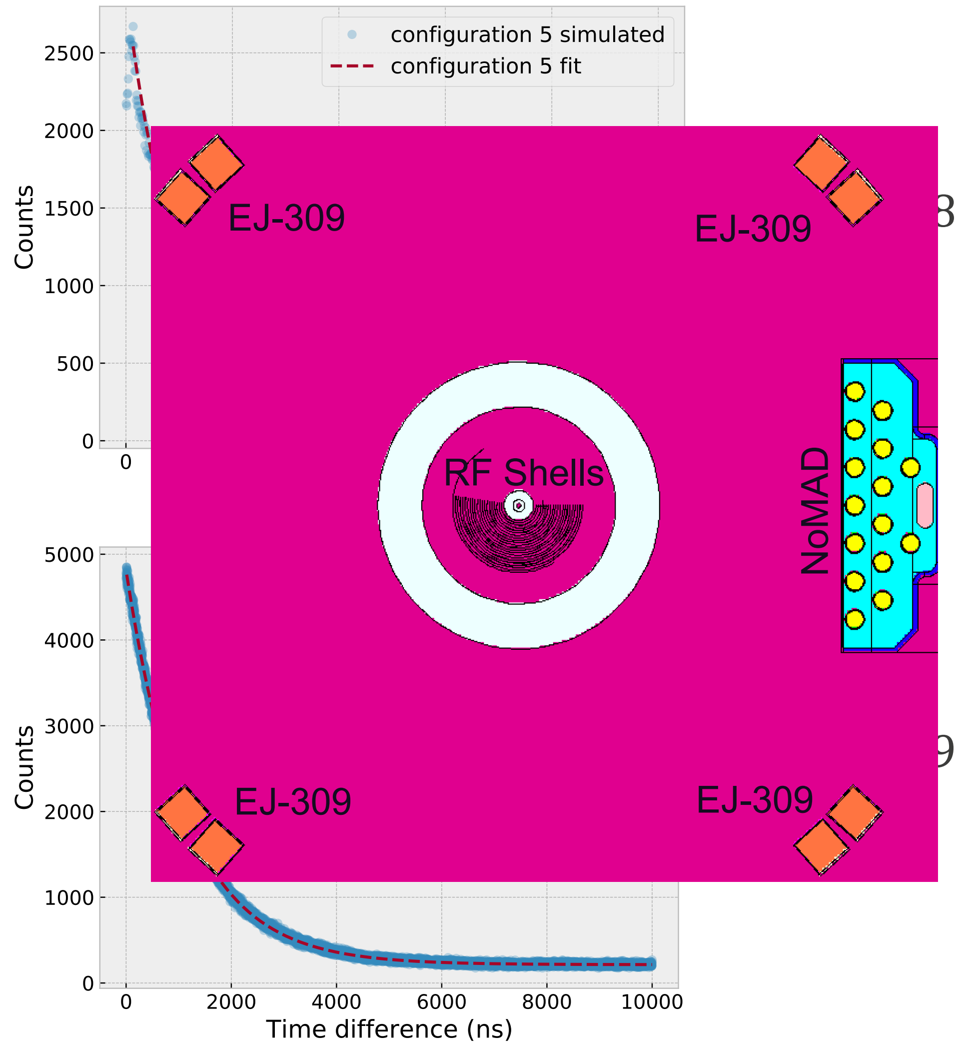
Simulations (KCODE, MCNPX-PoliMi)

- MCNP6 KCODE
  - Calculates k_{eff}
  - KOPTS card used to calculate β_{eff} and Λ
  - Reactivity and α:

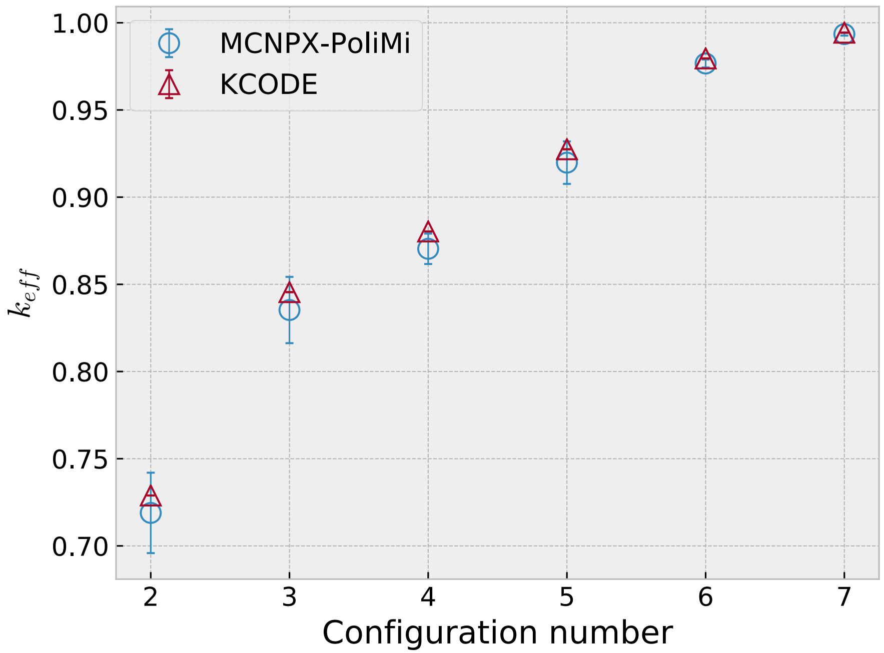
$$\rho = \frac{k_{eff} - 1}{k_{eff}} = \beta_{eff} - \alpha\Lambda$$

- MCNPX-PoliMi
  - Simulations of Rossi-α measurement
    - Same geometry as KCODE
    - Analysis is performed on event-by-event neutron interactions in the EJ-309 detectors
  - Fit to estimate α
  - Use β_{eff}, Λ from KOPTS



Rossi-α simulated results

- Good agreement between KCODE and PoliMi results
- Uncertainty in k_{eff} estimated with PoliMi is mostly attributed to the uncertainty in Λ calculated with KCODE
- Comparison to GODIVA IV measurements (also bare HEU)
  - $k_{eff} = 0.995$
  - $\alpha^{-1} = 1180\, ns$



Configuration	MCNP KCODE				MCNPX-PoliMi				
	α^{-1} (ns)	$\sigma_{\alpha^{-1}}$ (ns)	k_{eff}	$\sigma_{k_{eff}}$	α^{-1} (ns)	$\sigma_{\alpha^{-1}}$ (ns)	k_{eff}	$\sigma_{k_{eff}}$	χ^2
2	36	4	0.7289	3×10^{-5}	38.3	0.4	0.72	0.02	1.8
3	85	9	0.84455	4×10^{-5}	58.3	0.7	0.84	0.02	1.19
4	81	6	0.88034	4×10^{-5}	67.8	0.5	0.870	0.009	1.27
5	170	20	0.92745	4×10^{-5}	103.2	0.4	0.92	0.01	1.12
6	400	30	0.97956	4×10^{-5}	322.2	0.5	0.977	0.002	1.05
7	880	80	0.99432	4×10^{-5}	1177.2	0.6	0.9935	0.0008	1.01

Deviation from fit with decreasing effective multiplication

- Rossi-α method is only applicable over regions of reactivity where the point kinetic model assumptions are true

$$p(t) = Ae^{-\alpha t} + B \qquad [1]$$

Configuration	χ^2
2	1.8
3	1.19
4	1.27
5	1.12
6	1.05
7	1.01